Muon background simulations and Geant4

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Abstract

The process of gamma conversion into a pair of muons has recently been added as standard process to the Geant4 program. The main features of the process and the potential of Geant4 for combined machine/detector background simulations will be described.

1 INTRODUCTION, MOTIVATION

Whenever a high energy beam particle hits an obstacle and produces an electromagnetic shower, there is a small probability for muon production, of the order of $m_\mu^2/m_e^2 = 4.3\times10^{-4}$ per primary electron. The muon flux from collimation of halo particles can be substantial, like thousands per crossing. The muon background increases with beam energy (increased cross section, more secondaries) and high energy muons are more difficult to stop or sweep away. Muon background considerations should be part of the beam delivery and detector design, particularly for multi-TeV colliders projects like CLIC.

2 MUON BACKGROUND, GEANT3

The simulation started from the existing MUBKG code developed for TESLA [1]. MUBKG is based on muon production by MUCARLO [2–4] with cross sections from Tsai [5, 6]. The follow up of the muons through materials and the simulation of the energy loss was done with Geant3. The beam line geometry with magnets, fields and the tunnel geometry were hard coded (in FORTRAN), using the base line design for the CLIC beam delivery system (BDS) [7].

Fig. 1 shows tracks of muons, which were produced at the first, horizontal spoiler (SPX1) and which were able to reach the detector after about 3 km. The figure also shows the position of three optional, each 10 or 30 m thick, magnetized (2 T) iron "tunnel fillers" (TUF). They should be considered as a first trial of implementing a dedicated muon protection system and have not yet been optimized in properties and positioning.

The tracks that reached the detector region were further used as input for a Geant3 detector-simulation. Fig. 2 shows how a physics event with muon background may look like in a detector at CLIC[1].

Quantitative results of the beam delivery simulation are illustrated in Fig. 3. The results are given in terms of the ratio of beam particles removed by the collimation system with respect to the number of muons reaching the detector. For the last pair of spoilers (SPX4, SPY4) at about 500 m from the IP, the ratio reaches about 10^{-4}. Lowering the c.m. energy to 500 GeV increases the number of beam particles that can be collimated for a given muon flux in the detector by an order of magnitude. The dependence on the distance is weak, and we expect similar numbers for other collimation and final focus designs considered for CLIC [8, 9].

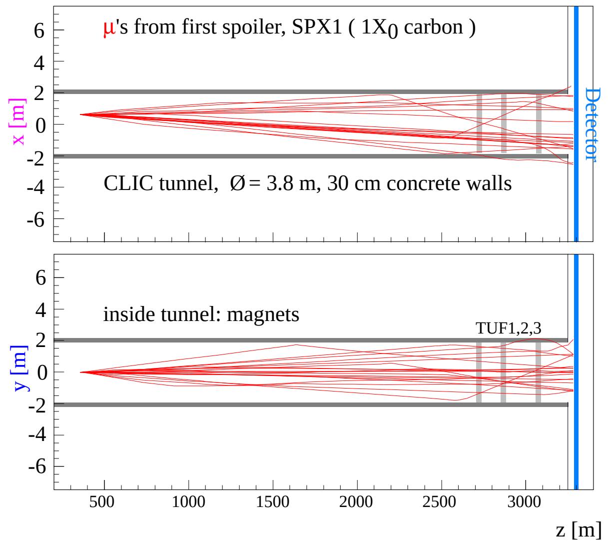

Figure 1: Tracking of muons, produced at the first spoiler, through the beam delivery system up to the detector region. Top is the horizontal and bottom the vertical plane.

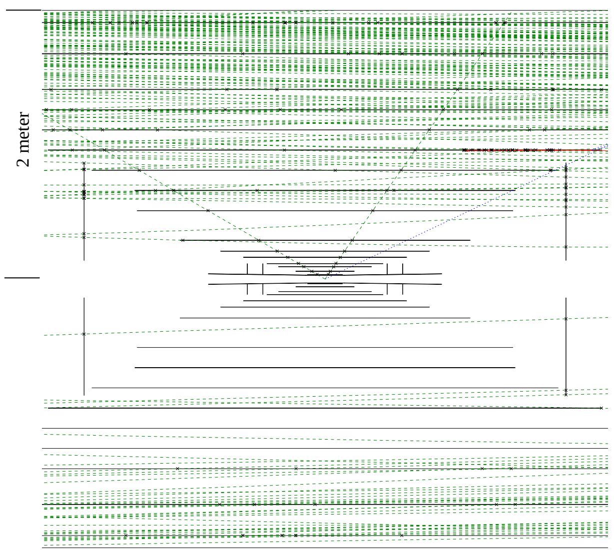

Figure 2: Physics event ($e^+e^- \rightarrow \tilde{\mu}\tilde{\mu} \rightarrow \chi_0\mu\chi_0\mu$) and muon background (in this case 1650 μ tracks) as seen in the detector simulation.

[1] Fig. 2 and the CLIC detector simulation were done by M. Battaglia, CERN.

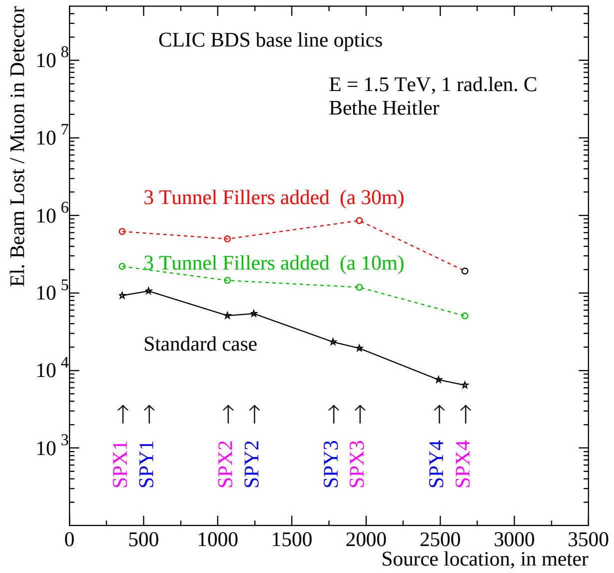

Figure 3: Number of lost electrons per muon passing through a detector with 7.5 m radius as a function of position along the baseline final focus. Potential collimator locations are indicated. The IP is at 3282 m.

For an estimate of the muon flux in the detector, assumptions have to be made about the fraction of halo electrons in the beam that will hit collimators. Here we assume a fraction of $f_{\rm tail} = 10^{-3}$, all hitting the first spoiler. With the parameters listed in Table 1, and for the two (e^+ and e^-) beams in CLIC we estimate that $2\,N_e\,N_b\,f_{\rm tail} c_\mu / r_{e\mu} \approx 2.7 \times 10^4$ muons reach the detector per bunch train crossing. With a muon protection system of three tunnel fillers (TUF), this would be reduced to 4000 muons per train (26 per bunch crossing).

Table 1: Parameters to estimate the muon flux at the detector

Parameter	symbol	value
Beam energy	E	1.5 TeV
Number of e^+, e^- per bunch	N_e	4×10^9
Bunches per train	N_b	154
Fraction of tail particles	$f_{\rm tail}$	10^{-3}
Secondaries and other processes	c_μ	2
e/μ ratio without TUF	$r_{e\mu}$	9.2×10^4
e/μ ratio with TUF	$r_{e\mu}$	6.2×10^5

The factor of $c_\mu = 2$ is based on more complete simulations for TESLA at 250 GeV and accounts for other muon production processes (mainly from secondary photons in the cascade and hadronic muon production) [1].

3 GEANT4 STUDIES

The techniques and structures of Geant3 have now been upgraded into Geant4 [10] which is an object-oriented package, written in C++. The Geant4 code will exist into the foreseeable future, forming the simulation framework for most of the LHC experiments in addition to some currently running ones.

More recently, the efficient methods of accelerator particle tracking based on transfer matrices have been included within the Geant4 framework into a program, `BDSIM` [11], that combines both the speed of accelerator-style particle tracking for particles in the accelerator beam pipe, with traditional Geant-style tracking when the particles pass through matter. In this way detailed studies of collimation efficiency are possible, including edge effects at element boundaries and particle interactions such as production and subsequent tracking of secondary particles in spoilers and collimators. Production of synchrotron radiation is another such process which, together with tracking of the synchrotron photons, enables accurate energy accounting for absorption in the beam pipe and accelerator elements.

The beam delivery systems of candidate linear colliders are currently undergoing frequent changes and optimizations and so `BDSIM` is set up to interface easily to already existing descriptions of beam lines. In this way a simple input file builds the entire beam line in Geant4 and this will allow comparative studies of collimation efficiency across the range of candidate machines, as well as optimisation of a given collimation system. An example of the use of `BDSIM` in studies of collimation efficiency have been demonstrated in [11]. In addition, a common bunch format has been incorporated [12] so that detailed descriptions of halo distributions can be utilised to explore any phase-space holes in the collimation efficiency.

4 IMPLEMENTATION OF MUON PRODUCTION PROCESSES IN GEANT4

The simulation of the energy loss of muons has been part of Geant distributions for many years already. It is somewhat surprising, that the electromagnetic production of muons instead had not been implemented.

My proposal to directly implement these processes into Geant4 was strongly supported by M. Maire, who chairs the Geant4 working group on electromagnetic processes. The work is done in close collaboration with S. Kelner and R. Kokoulin who have already been working on the energy loss of muons.

The main electromagnetic muon production process, the conversion of high energy photons into a pair of muons in the presence of nuclear fields is described in detail in [13] and has meanwhile been fully implemented into Geant4 and is now part of the standard distribution package.

In addition, the implementation of the process of annihilation of positrons with atomic electrons into muons, $e^+e^- \to \mu^+\mu^-$ has been started [14].

The first step for an efficient implementation of muon pair production by gamma conversion was to find a simple and still quite accurate description of the total cross section of the process. Fig. 4 shows the cross section normalized

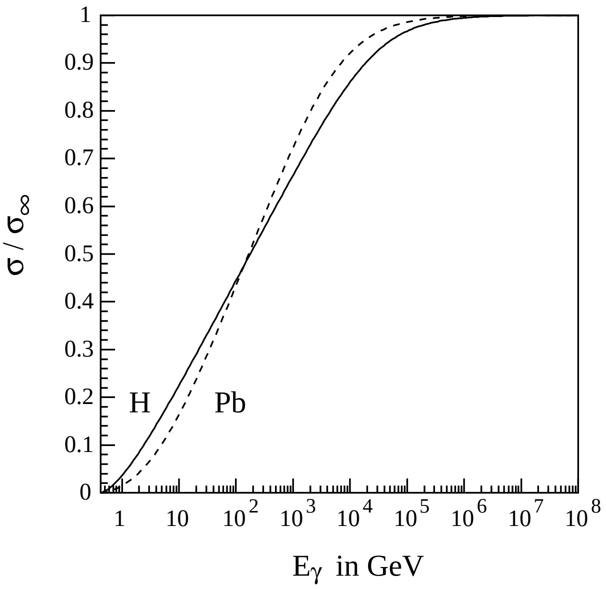

Figure 4: Total cross section for the Bethe Heitler process $\gamma \rightarrow \mu^+\mu^-$ as function of the photon energy E_γ in hydrogen and lead, normalized to the asymptotic cross section σ_∞.

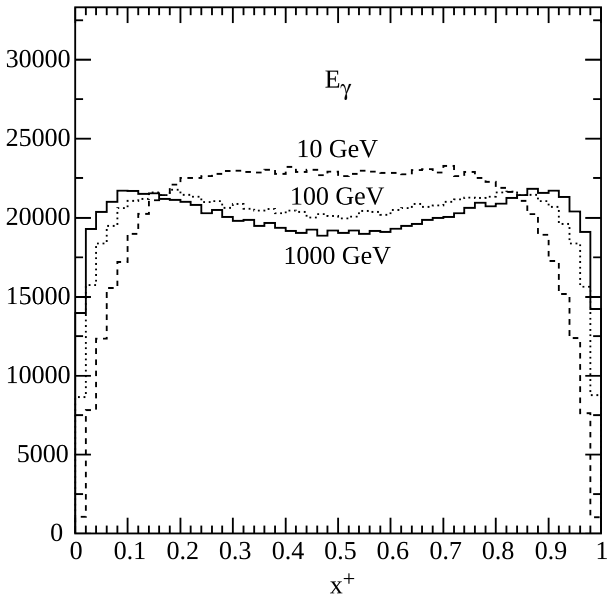

Figure 5: Histogram of generated x_+ distributions for Beryllium at three different photon energies. The total number of entries at each energy is 10^6.

to the high energy asymptotic cross section. The next step is to determine the energy sharing between the two muons. Generated distributions in terms of x^+ (μ^+ energy normalized to the initial γ energy) are shown in Fig.5.

The scattering angles in the laboratory system are of the order of $1/\gamma$. The distribution of scattering angles θ^+ of the μ^+ in the laboratory system, multiplied with its Lorentz factor γ^+ is shown Fig. 6.

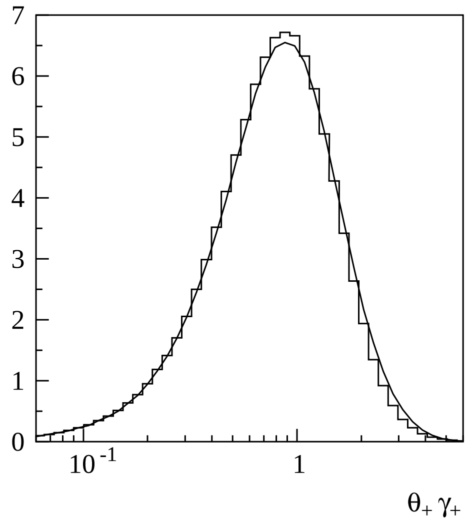

Figure 6: Angular distribution in logarithmic scale. The curve corresponds to the exact calculations and the histogram is the simulated distribution.

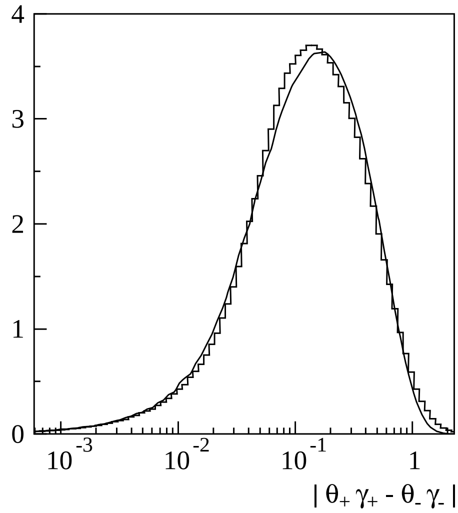

Figure 7: Distribution in the difference of transverse momenta of positive and negative muons (with logarithmic x-scale).

The momentum transfer to the nucleus (recoil correction) is taken into account in the generation of the angular variables. Fig. 7 shows the differences between μ^+ and μ^- scattering angles. Without recoil correction by the nucleus, this difference would be zero. A detailed description with all relevant formulas is given in [13] and also included in the physics reference manual distributed with the Geant4 code.

Together with the already existing electromagnetic cascade and energy loss code, the recently added muon production processes now allow for accurate modelling of electromagnetic cascades including muons in Geant4.

The full simulation for the beam delivery system can be rather time consuming. The speed was increased significantly by cutting low energy (below some GeV) particles. The simulation of 10 000 1.5 TeV electron cascades and their tracking through the beam-delivery requires some hours of CPU on a current desktop computer.

First, preliminary results are shown in Fig.8, where the muon production from a 1.5 TeV electron beam, which impinges completely on the energy spoiler, is shown for a variety of cases. These first results indicate that the thickness and magnetisation of the magnet elements have significant effects on the total muon rate at the detector, as does the effect of production of muons by secondaries in showers. The fact that the final muon rate can vary by more than an order of magnitude depending on the details of these effects, stresses the need for full simulations for the eventual reliable determination of background rates at the linear collider.

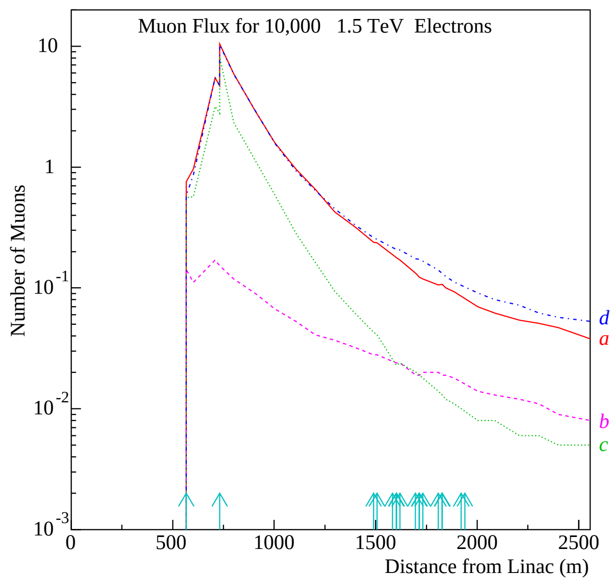

Figure 8: Muon flux determination from Geant4 for a 1.5 TeV beam with a -2% offset in energy. The positions of the spoilers and collimators are shown by arrows. Case *a* corresponds to magnet elements consisting of unmagnetised (and case *d* magnetised) cylinders of iron of diameter 20 cm with fully simulated showers. Case *b* is as case *a* except that only the first photon of a shower contributes. Case *c* is the same as case *a* except the magnet elements have diameter 50 cm.

5 SUMMARY

We performed background studies using Geant for the CLIC beam delivery system. The rate of muons, produced as secondary particles in the collimation of high energy (1.5 TeV) electrons can be substantial and will add to the challenges to obtain clean nanometre beam collisions. A good simulation that includes production and tracking of background particles with interactions in matter is required.

In addition to dedicated muon production and follow up of secondaries with Geant3 for a single fixed geometry, we have extended Geant4 such, that tracking through the machine lattice and materials is done in a combined, flexible way. The simulation of the geometry can be built automatically using existing (MAD-like) machine descriptions. This allows for background optimisation during machine design.

6 REFERENCES

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